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THE INTERACTION AND VARIATION OF WAVES AND TURBULENCE
FROM MST RADAR DATA. (U) CONTROL DATA CORP MINNEAPOLIS
MN METEOROLOGY RESEARCH CENTER. G D NASTROM 27 NOV 85

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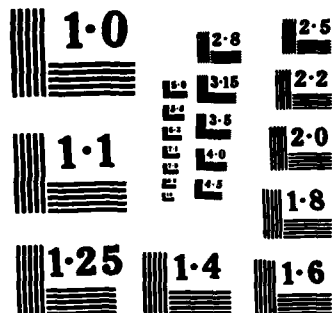
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<p>This report summarizes research results obtained using data from clear-air Doppler radars in Alaska, Colorado, and France. Among other variables, these radars measure the vertical velocity over the height range from about three to twenty kilometers. A brief climatology of the variability of vertical velocity was prepared, including a study of its relationship to synoptic weather events. Comparisons of the time-averaged vertical velocity to estimates of the vertical velocity computed from the equations of motion and routine meteorological data showed that these radars provide a measure of the sub-synoptic scale vertical velocity of the atmosphere, at least under certain conditions. Details of the echoing mechanism for vertically directed antenna systems were studied to help interpret the measurements. Another variable provided by MST radars is the backscattered echo power, which is directly related to the refractivity turbulence structure constant (C-sub-n-squared) when the antenna beam is not directed vertically. Case studies made using a network of radars in Colorado have shown that gravity waves and refractivity</p>					
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turbulence can be initiated apparently simultaneously in the strong shear region near the edge of a jet stream. The diurnal variation of backscattered power shows a maximum in the daytime in the troposphere, but a reversed pattern in the stratosphere. A climatology of refractivity turbulence was prepared, including a brief study of its relationship to other meteorological variables. The frequency distribution was found to be log-normal, which has important application for data handling both in initial data processing and in scientific analyses. The frequency power spectrum of refractivity turbulence was found to have a universal shape with altitude, station, and season, and has only small changes in amplitude with space or time.

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THE INTERACTION AND VARIATION OF WAVES AND TURBULENCE
FROM MST RADAR DATAFinal Technical Report
Contract F49620-82-C-0029
G. D. Nastrom

A. RESEARCH OBJECTIVES (STATEMENT OF WORK):

1. Prepare a brief climatology of vertical velocities at Poker Flat, Alaska, from MST Doppler radar data, and to compare the radar vertical velocities with indirectly computed vertical velocities.
2. Compare the vertical velocities measured with the ST radars at Poker Flat, Platteville (Colorado), and ALPEX (France), with indirectly computed vertical velocities to determine the synoptic conditions under which the two data sets give comparable results.
3. Draw conclusions regarding the interpretation of MST/ST radar-measured vertical velocities as synoptic-scale velocities, based on the above comparison studies.
4. Examine the cross-correlation functions of MST/ST radar winds and nearby radiosonde winds at Poker Flat and Platteville and estimate space and time scales over which a single observation can be considered representative within given bounds.
5. Use data from Poker Flat and Platteville radars to make case study comparisons of small-scale turbulence and gravity wave activity during various synoptic conditions and analyze interactions between the small-scale turbulence and gravity waves as functions of the background flow.
6. Use network radar data from Colorado to determine joint space and time relationships of the occurrence of waves and turbulence under different synoptic conditions.
7. Analyze the variability of the refractive structure constant under different synoptic conditions and at stations in different terrain.
8. Determine, from Poker Flat and Platteville long term data, apparent diurnal and seasonal variation in the structure constant.
9. Examine the frequency spectrum of C_n^2 as a function of location, altitude, and season to see if its shape and amplitude appear universal. Compare the observed shape with predictions from wave and turbulence theories.

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B. STATUS OF THE RESEARCH EFFORT:

1. A brief climatology of the vertical velocity at Poker Flat from MST radar data was given in refs. 2 and 15. It was found that the frequency distribution of vertical velocity can be approximated as the sum of two normal distributions, one of which has variance about an order of magnitude larger than the other. This dichotomy reflects the occurrence of so-called quiet and active periods observed in the time series of vertical velocities. The active periods correlate well with strong horizontal winds at the local terrain height (near 3 km at Poker Flat), suggesting that the enhanced variance is due to gravity waves launched by flow over rough terrain. This result supports similar interpretation given earlier from case study analyses. A second source of enhanced variance is convective activity, and the typical standard deviation of vertical velocity is nearly twice as large during the summer as other seasons. Long-term mean values of vertical velocity are near zero (as expected for mass balance) and show no obvious pattern except on a diurnal basis. The vertical velocities in summer have a pronounced diurnal variation over Poker Flat, with maximum downdrafts during the afternoon and amplitudes of a few cm/s in the mid-troposphere. This variation is believed to arise from mountain-valley circulations. The autocorrelation function of vertical velocity is that of a mixed moving-average autoregressive process. The time between independent observations of the vertical velocity, determined from the autocorrelation function, is found to be about 15 minutes during active periods and about 9 minutes during quiet periods (ref. 15). The frequency power spectrum of vertical velocity (ref. 11), which is the Fourier transform of the autocovariance function, is found to have a universal character. The shape of the spectrum during quiet periods is nearly flat, following an f^{-2} power law relation with frequency, below the Brunt-Vaisala frequency, and then decreases quickly at higher frequencies. The shape and amplitude are very similar at stations in the arctic, mid-latitudes, and tropics. During active periods the spectrum contains much more energy, especially at longer periods, and the slope approaches $-5/3$ which is similar to the slope of the spectrum of horizontal wind. The interpretation of the spectrum remains a topic of discussion, and most efforts so far have relied on the theory of

quasi-two-dimensional turbulence and the theory of internal waves (ref. 4, 10, 17, and 19). The vertical velocity spectrum observed during quiet periods is widely believed to represent a spectrum of internal waves. The spectrum during active periods, as well as the horizontal velocity spectrum, is in many respects more consistent with a quasi-two-dimensional turbulence spectrum than a wave spectrum.

2. Comparisons of the time-averaged (3- to 9-hour averages) vertical velocities at Platteville, Poker Flat, and from Alpex with vertical velocities computed using NMC data and the equations of motion have been made (refs. 1,3,5,6,7, and 16). It was found that during active periods the radar mean vertical velocities were often biased by standing lee waves, and that the radar data were representative of only a small local area. Further, the variance of the vertical velocity during active periods is so large that the mean could not be determined with sufficient statistical confidence to be useful. However, on a long-term basis the bias due to lee waves averages toward zero, and the radar data are useful for climatological studies of vertical velocity patterns (ref. 6).

3. During quiet periods the standard error of the mean for 9-hour averaged vertical velocity is typically 2 cm/s. During these periods the vertical velocities measured by the radars and computed from radiosonde data usually agree within this limit (ref. 6). During some cases the radar values are larger, indicating that the radar data are representative of sub-synoptic scale motion systems, rather than synoptic-scale systems. Results from the radar network operated in France during Alpex indicate the spatial scale of the vertical motions measured by the radar is considerably larger than 50-km radius.

4. Rather than using horizontal winds measured over the radar and from distant balloon stations, the study was made using vertical velocity data measured over the radar by two independent radar techniques (ref. 13,21, and 23). A lingering question concerning the interpretation of vertical velocities measured with a vertically directed beam was addressed. The issue was whether or not quasi-specular reflections from tilted layers moving over the radar lead to a contamination of vertical velocity measurements by the horizontal velocity. No evidence of contamination was found.

5. Case study comparisons of the interaction of small-, meso-, and large-scale motion systems have been made (ref. 14 and 20). The most striking feature of these results is the evidence that gravity waves and small-scale turbulence can be launched simultaneously in the free atmosphere, near the edge of an approaching jet stream. In one approximately nine-hour period, as the horizontal winds over Platteville near the tropopause increased from 25 to 45 m/s, the standard deviation of vertical velocity showed a sudden burst of activity emanating upward from near the 8-km level. At the same time the backscattered power near the 8-km level increased by nearly 10 dB, clearly demonstrating the link between local generation of gravity waves and small-scale turbulence.

6. Stations from the Colorado Profiler Network have been used to examine the effects of underlying terrain on backscattered power under differing synoptic weather conditions (ref. 20). It is found that the strength of small-scale turbulence is closely related to the zonal wind speed, i.e., the wind across the mountains. The response to increased winds is stronger at stations very near the mountains than for Fleming, which is located in the high plains. Using the standard deviation of vertical velocity as an indicator of gravity wave activity, it was found that waves and turbulence can be generated simultaneously, and that the episodes of enhanced turbulence appear at all stations in the Network at nearly the same time. This result indicates that the enhanced turbulence occurs on scales at least as large as the Network, and is not a highly local phenomena; this is of importance for future parameterization in models of energy loss due to turbulence.

7. A climatology of C_n^2 has been prepared (ref. 12 and 18). Data from Poker Flat and Platteville were used. Principal results include an extensive demonstration that the frequency distribution of C_n^2 is log-normal. This finding has important consequences for the initial processing of radar echoes, as well as for the scientific analysis of C_n^2 . The autocorrelation function of $\log C_n^2$ can be modeled as the product of a first-order autoregressive process and a random process. The associated integral time scale, an indicator of the time between statistically independent observations of $\log C_n^2$, decreases with altitude from 25-45 minutes in the troposphere to about 18 minutes

in the stratosphere. The power spectrum of $\log C_n^2$ follows a power law relation with frequency: at periods greater than about 2 hours the spectral slope is near $-5/3$ and at periods less than 2 hours the slope is near -1 . Monthly mean values of $\log C_n^2$ are largest in the winter, and show a secondary maximum in summer. The winter peak is apparently related to increased jet stream and baroclinic storm activity, and the summer peak is believed to be due to convective activity. The correlation of three-hourly values of $\log C_n^2$ with wind speed over month-long periods ranges as high as 0.8 and has a median value near 0.3. During certain periods, C_n^2 also depends on other meteorological variables such as boundary layer inversions and gravity wave activity. Monthly mean values of $\log C_n^2$ correlate more closely with an indicator of the intensity of gravity wave activity than with wind speed or the coarse-scale wind shear. The mean value of $\log C_n^2$ decreases about 2 dB/km with height.

8. The diurnal and seasonal variations of C_n^2 have been determined using backscattered power data from Poker Flat and stations in the Colorado Profiler Network (ref. 9 and 12). A statistical analysis of these data shows there is a significant diurnal variation during the summer months. In the midtroposphere the diurnal range is near 7 dB with largest values in the afternoon, and probably arises from the enhanced turbulence and moisture levels due to convection. In the stratosphere in Colorado, the diurnal range is about 5 dB, with smallest values in the afternoon. The stratospheric cycle is interpreted as a response to modulation of the amplitude of gravity waves propagating upward from the troposphere. The diurnal cycle at all heights becomes indistinct during the winter months.

9. The frequency power spectrum of $\log C_n^2$ at Poker Flat and Platteville has been studied (ref. 22). Variations of spectral shape as a function of location, season, altitude, or speed of the background wind in the upper troposphere are very small, suggesting that the shape is a universal function. Spectral amplitude changes are also relatively small; the largest difference found is about 3 dB increase from winter to summer. The shape of the spectrum is that of a power-law dependence on log frequency, and has a slope near $-5/3$ at periods longer than about 2 hours and a slope near -1 at shorter periods. The $-5/3$ slope region is

reminiscent of the shape of the spectra of horizontal wind and temperature; the latter appear to be most consistent with a spectrum of quasi-two dimensional turbulence, but are also held to arise from a spectrum of internal waves. It is found that -1 slope regions have been detected in the spectra of winds near the tropopause in the vicinity of patches of clear-air turbulence encounters by aircraft, in the spectra of ozone near the tropopause, in the spectra of radial wind velocity as observed by MST radars, and in the spectra of wind velocity in the earth's boundary layer. There do not appear to be any extant theories which could readily be applied to explain the -1 slope region.

C. PUBLICATIONS:

1. "Detection of synoptic-scale vertical velocities using an MST radar," G.D. Nastrom, Geophys. Res. Lett., 11, 57-60 (1984).
2. "A brief climatology of vertical wind variability in the troposphere and stratosphere as seen by the Poker Flat, Alaska, MST radar," G.D. Nastrom and K.S. Gage, J. Clim. Appl. Meteor., 23, 453-460 (1984).
3. "Synoptic-scale dynamics with vertical velocity," G.D. Nastrom, Handbook for MAP, vol. 14, 62-69 (1984).
4. "On the spectrum of atmospheric velocity fluctuations seen by MST/ST radar and their interpretation," K.S. Gage and G.D. Nastrom, Handbook for MAP, vol. 14, 197-207 (1984).
5. "Measurements of vertical velocity over flat terrain by ST radar and other related uses of the radar data set," J.L. Green and G.D. Nastrom, Handbook for MAP, vol. 14, 364-366 (1984).
6. "Direct measurement of large-scale vertical velocities using clear-air Doppler radars"; G.D. Nastrom, W.L. Ecklund, and K.S. Gage, Mon. Wea. Rev., 113, 708-713 (1985).
7. "Relationship of precipitation to vertical motion observed directly by a VHF wind profiler during a spring upslope storm near Denver, Colorado," K.S. Gage and G.D. Nastrom, Bull Amer. Meteor. Soc., 66, 394-397 (1985).
8. "Waves and turbulence from MST radar data," G.D. Nastrom, Final Technical Report (this report) (1985).
9. "The diurnal variation of backscattered power from VHF Doppler radar measurements in Colorado and Alaska," G.D. Nastrom, W.L. Ecklund, K.S. Gage, and R.G. Strauch, Radio Science, in press (1985).

10. "On the spectrum of atmospheric velocity fluctuations seen by MST/ST radar and their interpretation," K.S. Gage and G.D. Nastrom, Radio Science, in press (1985).

11. "A preliminary climatology of the spectrum of vertical velocity observed by clear-air Doppler radar," W.L. Ecklund, K.S. Gage, G.D. Nastrom, and B.B. Balsley, J. Clim. Appl. Meteor., in press (1985).

12. "The variability of turbulence, 4 to 20 km, in Colorado and Alaska from MST radar observations," G.D. Nastrom, K.S. Gage, and W.L. Ecklund, J. Geophys. Res., submitted (1985).

13. "A comparison of vertical velocities measured by a VHF radar with specular and non-specular echoes," J.L. Green, W.L. Clark, J.M. Warnock, and G.D. Nastrom, Geophys. Res. Lett., submitted (1985).

D. LIST OF PROFESSIONAL PERSONNEL:

Dr. Gregory D. Nastrom, Principal Investigator

Mr. Dale N. Hovland, Computer Systems Expert

E. INTERACTIONS:

1. Papers given at Meetings, etc.:

14. "Vertical wind variability and turbulence as seen by the Poker Flat, Alaska, MST radar," K.S. Gage and G.D. Nastrom, 18th General Assembly of IUGG, Hamburg, (1983).

15. "A brief climatology of vertical air motions from MST radar data at Poker Flat, Alaska," G.D. Nastrom and K.S. Gage, Proceedings 21st Conference on Radar Meteorology, Edmonton, pp. 135-140 (1983).

16. "On the measurement of synoptic-scale vertical velocities by ST/MST radar," G.D. Nastrom and K.S. Gage, Proceedings 22nd Conference on Radar Meteorology, Zurich, pp. 456-460 (1984).

17. "On the interpretation of the variance spectrum of velocity observed by ST/MST radar," K.S. Gage and G.D. Nastrom, Proceedings 22nd Conference on Radar Meteorology, Zurich, pp. 482-487 (1984).

18. "Doppler radar measurements of turbulence in the clear air," G.D. Nastrom, K.S. Gage, and W.L. Ecklund, Proceedings 7th Conference on Turbulence and Diffusion, Boulder, pp. 35-38 (1985).

19. "Evidence for coexisting spectra of stratified turbulence and internal waves in mesoscale atmospheric velocity fields," K.S. Gage and G.D. Nastrom, Proceedings 7th Conference on Turbulence and Diffusion, Boulder, pp. 176-179 (1985).

20. "Interactions of small-, meso-, and large-scale flow features from VHF radar observations," G.D. Nastrom, 5th Conference on Meteorology of the Stratosphere and Mesosphere, Boulder (1985).

21. "Comparison of vertical velocities measured by an MST radar with specular and non-specular echoes," J.L. Green, G.D. Nastrom, W.L. Clark, and J.M. Warnock, International Geoscience and Remote Sensing Symposium, Amherst (1985).

22. "The frequency spectrum of C_n^2 from MST radar data," G.D. Nastrom, Proceedings 3rd Workshop on Technical and Scientific Aspects of MST Radar, Aguadilla, to appear (1985).

23. "A comparison of vertical velocities measured by a VHF radar with specular and non-specular echoes," J.L. Green, W.L. Clark, J.M. Warnock, and G.D. Nastrom, Proceedings 3rd Workshop on Technical and Scientific Aspects of MST Radar, Aguadilla, to appear (1985).

2nd Workshop on Technical and Scientific Aspects of MST Radars, Urbana, 1984 (see ref. 3,4,5)

2. Consultative and Advisory Functions:

- (a) The Principal Investigator served as a member of a Delphi study group to identify emerging technologies with the potential for rapid advancement toward practical use which was conducted under sponsorship of the Under Secretary of Defense, Research and Engineering, by Science Applications International Corporation. This activity took place during the spring of 1985, and was all conducted by phone or mail.
- (b) A close collaborative relationship has existed with scientists at the Aeronomy Laboratory and the Wave Propagation Laboratory of NOAA. Much of this work was aimed at topics of general scientific interest, as evidenced by the list of publications and papers, while some work was concerned with technical issues of radar operations. For example, an algorithm was developed to automatically edit

radar data with nearly the same degree of confidence as achieved by an experienced scientist doing hand-editing. The results of this, and similar informal yet useful studies, were shared with scientists at the AL and WPL for use in designing future radar systems.

- (c) The PI presented Atmospheric Physics Seminars at the University of Minnesota on the topics of vertical velocity (autumn, 1983) and C_n^2 (spring, 1984).

F. PATENT APPLICATIONS: None

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